# DRACO: DIDYMOS RECONNAISSANCE AND ASTEROID CAMERA FOR OP-NAV.

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**Introduction:** The Double Asteroid Redirection Test (DART) [1] is a low-cost mission concept developed in response to the threat of an asteroid impact and the need to mitigate such a threat. In particular, the *NRC Defending Planet Earth* report [2] recommended that "the first priority for a space mission in the mitigation area is an experimental test of a kinetic impactor along with a characterization, monitoring, and verification system." DART is designed to be the first planetary defense demonstration of the kinetic impactor concept, the impulsive deflection of an asteroid.

The DART target is the binary asteroid system 65803 Didymos. The primary member of the binary system (Didymos A) has a diameter of 780 m, the secondary member (Didymos B) has a diameter of 160 m, and the two objects are separated by roughly 1.2 km with an orbital period of 11.9 hrs [3]. The Didymos system is the ideal target because: 1) Didymos is highly accessible with a close pass by Earth in 2022. 2) The DART impact produces a change in the Didymos binary orbit period that can be measured from Earth-based observations during its close pass. 3) Didymos B is of a size typical of potentially hazardous asteroids (PHA) and likely an S-type asteroid, suggesting that its composition and physical properties are shared by a large fraction of PHAs. DART is planned to impact Didymos B at ~6 km/s in October 2022.

The sole payload instrument on DART is DRACO, the Didymos Reconnaissance and Asteroid Camera for Op-nav. Here, we describe DRACO's responsibilities on the DART mission, the resulting design, and the planned operations.

**DRACO Requirements:** DRACO's highest priority is to support onboard navigation and terminal guidance to ensure the DART spacecraft impacts Didymos B. DRACO images will feed directly into onboard software that will autonomously target Didymos B. At 30 days prior to DART impact, DRACO will be able to image the Didymos system with a signal/noise ratio to support this onboard navigation need.

In addition, DRACO images will characterize the Didymos system and provide detailed views of the DART impact site. The final DRACO images returned prior to impact will resolve features within the impact site at a smaller scale than the impacting DART spacecraft, providing important constraints for modeling efforts to interpret the results of the DART hypervelocity impact event.

**DRACO Overview:** DRACO (Fig. 1) is derived from the Long Range Reconnaissance Imager (LORRI) instrument on New Horizons. DRACO is required both to image the Didymos system 30 days in advance, when the target is faint, and to image the impact site shortly before impact, when the scene is considerably brighter. DRACO uses a complementary metal–oxide–semiconductor (CMOS) detector to support <1 ms exposure times for the final images prior to impact to avoid saturation, a capability not supported by the LORRI charge-coupled device (CCD) detector. The CMOS detector chosen for DART also costs significantly less than the LORRI detector and maintains the low noise and high sensitivity needed for faint imaging. DRACO is mounted inside the spacecraft structure via a support ring and flexures to the spacecraft.

**DRACO Optics:** DRACO optics are based on the optical design from LORRI, which consists of a f/12.6 Ritchie-Chrétien telescope with an aperture of 208 mm [4]. LORRI operated in a varying thermal environment from 1 AU to over 30 AU while DART remains ~1 AU from the sun for the duration of the mission. This more stable thermal environment allows DRACO optics to be made from Al rather than LORRI's SiC, re-

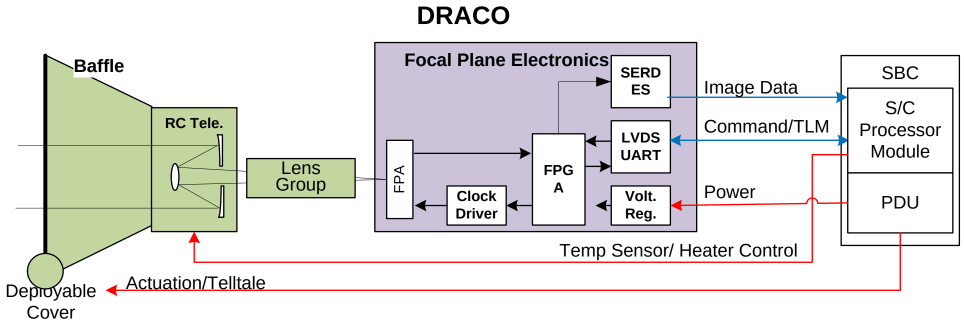

**Figure 1.** DRACO block diagram

ducing cost and complexity. Other changes include removal of image ghosts via planned changes to the field-flattening lens group [4].

**DRACO Electronics:** The DRACO detector is the BAE sCMOS CIS2521, which is a 2560x2160 format, has 6.5 um 5T pixels and has low (<5e-) read and dark noise. The CIS2521 has been radiation tested up to 50 krad, the maximum dose possible for DART, and the corresponding dark current increases have been characterized [5]. The detector is digitized on chip with two different gain states, a high-gain and a low-gain mode, each with 11 bits. The detector data are sent to the DRACO Focal Plane Electronics (FPE), which also commands and provides power to the detector. The FPE takes the two 11 bit pixel streams and converts them into a single 16 bit stream.

The FPE passes image data to the Single Board Computer (SBC), which hosts the DART processing. The SBC is built around the UT700 LEON3 processor and an RTG4 FPGA for supporting firmware. It also includes MRAM for hosting the software image, 32 MB of SRAM for processing and 16 GB of flash storage. The SBC also sends commands and receives telemetry from the FPE as it hosts all instrument software.

**DRACO Processing:** DRACO processing will have many options for reducing data volume due to limited time to return images prior to final impact with Didymos B. These include: 2x2 pixel binning, reduction to 12b data, lossless image compression algorithms, and windowing of the image. In addition to these, DRACO will process images for background removal and bad pixel removal. All of these processing steps occur in the firmware inside the RTG4.

Additionally, the images from DRACO will be used in closed-loop terminal guidance to Didymos B. Flight software handles the guidance and navigation filters, but DRACO is responsible for thresholding, blobbing, and centroiding the images in the RTG4 firmware in a single-pass approach [6]. DRACO creates a bitmask of pixels above a threshold signal, looks for contiguous pixels to group together in blobs, and identifies the centroid of the blob. These centroids are passed to the navigation software.

**DRACO Operations:** DRACO operations support the characterization of the Didymos system and the impact site and can be considered in two main phases: long-range imaging, conducted when the Didymos system is not resolvable, and proximity imaging, when Didymos A and B can be distinguished

Long-range imaging observations will begin approximately 30 days before impact to provide ground based optical navigation images which include Didymos and at least 3 stars. These data will be downlinked to Earth for navigation's processing and will also be used to refine the rotation rate of Didymos A and the orbit of Didymos B, complementing Earth-based observations. These images will also enable a search for any additional members of the Didymos system.

Beginning at roughly 4 hrs prior to impact, DRACO can separate Didymos A and B, and by about 1 hr prior, Didymos B becomes a resolved object. Starting at 4 hrs before impact, DRACO is targeted on Didymos B, and DRACO processes images to pass centroids to navigation for closed-loop control to the target system. As many images as the available downlink supports will also be sent to Earth, estimated at roughly one image every 5 s. These proximity imaging observations will provide information about the shapes of the two objects and their geologic properties. The hemisphere of Didymos A visible to DRACO will be imaged with meter-sized pixel-scales. Figure 2 provides a modeled DRACO view of the Didymos system two minutes prior to impact. The final set of images obtained by DRACO will be of the DART impact site on Didymos B, and the final image returned to Earth will be acquired at 20 cm/pixel or better.

An operational test of the onboard autonomous targeting software is planned to be conducted prior to DART's impact of Didymos B, during an opportunistic asteroid flyby during DART's cruise to the Didymos system, currently planned for near-Earth asteroid 2001 CB21 in March 2022. DRACO inflight calibrations will utilize the Moon and imaging of star fields. All inflight calibration and Didymos system characterization images will be returned to Earth for analysis

**Figure 2.** A modeled DRACO view of the Didymos system two minutes prior to DART impact.

**References:** [1] Cheng A. F. et al. (2016) *Planet. Space Sci., 121*, 27-35. [2] National Research Council (2010) *Defending Planet Earth*, National Academies Press, 152 pp. [3] Michel P. et al. (2016) *Adv. Space Res., 57,* 2529-2547. [4] Cheng A. F. et al. (2008) *Space Sci Rev. 140*, 189-215. [5] Rodricks B. et al. (2010) *Proc. SPIE 7805* [6] Trein J. et al. (2008) *MPC-Workshop, Ravensburg-Weingarten*, 71-77.